Dynamic Finite Element Predictions for Mars Sample Return Cellular Impact Test #4

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Abstract

The nonlinear, transient dynamic finite element code, MSC.Dytran, was used to simulate an impact test of an energy absorbing cellular structure. This pre-test simulation was performed to aid in the design of an energy absorbing concept for a highly reliable passive Earth Entry Vehicle (EEV) that will directly impact the Earth without a parachute. In addition, a goal of the simulation was to bound the acceleration pulse produced at impact and transmitted to the simulated space cargo container. EEV's are designed to return materials from asteroids, comets, or planets for laboratory analysis on Earth. The EEV concept uses an energy absorbing cellular structure designed to contain and limit the acceleration of space exploration samples during Earth impact. The spherical shaped cellular structure is composed of solid hexagonal and pentagonal foam-filled cells with hybrid graphite-epoxy/Kevlar cell walls. Space samples fit inside a smaller sphere at the center of the EEV's cellular structure. The material models and failure criteria in the finite element model were varied to determine their effect on the resulting acceleration pulse. Pre-test analytical predictions using MSC.Dytran were compared with the test results obtained from cellular impact test #4 using a bungee accelerator located at the NASA Langley Research Center's Impact Dynamics Research Facility. The material model used to represent the foam and the proper failure criteria for the cell walls were critical in predicting the impact loads of the cellular structure. It was determined that a FOAM1 model for the foam and a 20% failure strain criteria for the cell walls gave an accurate prediction of the acceleration pulse for cellular impact test #4.

Introduction

The Earth Entry Vehicle (EEV) concept is designed to return materials from asteroids, comets, or planets to Earth. One concept for a Mars Sample Return EEV developed at NASA Langley Research Center, and illustrated in Figure 1, is a circular aeroshell structure approximately one meter in diameter with an energy absorbing impact sphere in the center of the vehicle. The impact sphere is constructed of three-dimensional cells with hybrid graphite-epoxy/Kevlar walls, each cell filled with a low-density energy absorbing carbon foam. This simple, highly reliable, and cost-effective EEV is designed to withstand a terminal velocity land impact without a parachute[1]. The nominal impact surface for an EEV would be soft clay soil[2]. Design criteria for the EEV concept require
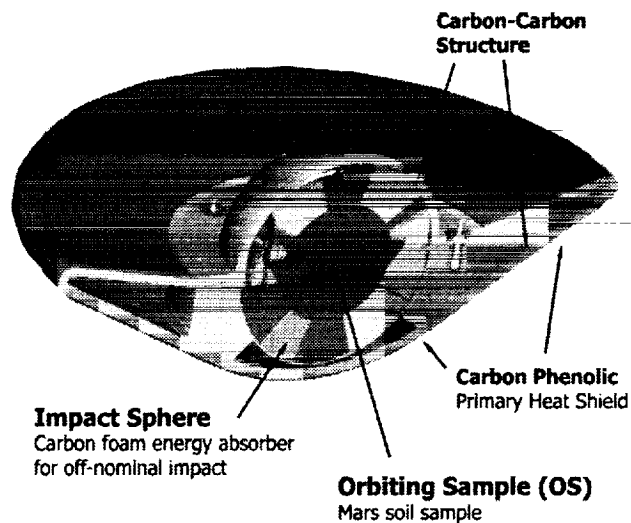
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Figure 1 – Schematic of candidate Mars Sample Return Earth Entry Vehicle.

that sample containment be assured with high levels of reliability. Thus, an energy absorbing impact sphere has been designed to limit the acceleration of the Mars samples and to provide a high level of containment in case Earth impact should occur on a rigid surface outside the soft clay target.
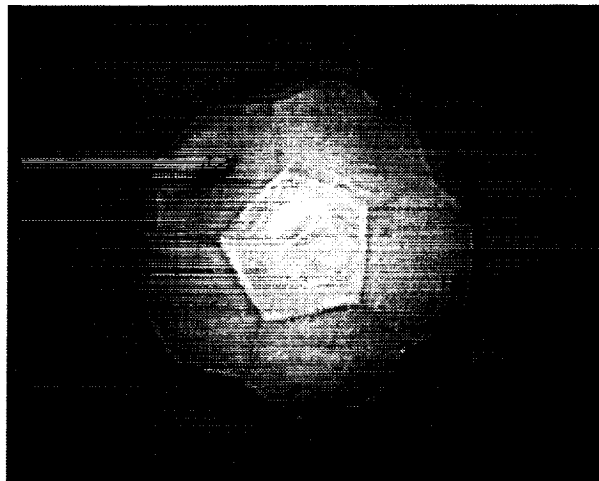

Figure 2 – Bottom view of cellular structure showing shape and geometry of the cells.

The current concept of the energy absorbing impact sphere is a composite cellular structure made with energy absorbing materials that limits the acceleration of the space samples and ensure containment. The cellular structure, shown in Figure 2, is composed of cells that are filled with energy absorbing foam and enclosed with hybrid composite cell walls. Energy absorbing materials include carbon foam, Kevlar, graphite, and hybrid Kevlar-graphite composites. Rock, soil, and atmospheric samples may be kept within the cellular structure in a sample container designated the Orbiting Sample (OS), as indicated in Figures 1 and 3.

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The nonlinear finite element program MSC.Dytran[3] was used to predict the acceleration pulse and deformations for impact test #4 of an energy absorbing cellular structure. The required reliability and containment assurance criteria are being addressed, in part, by performing nonlinear dynamic finite element simulations of the impact of the EEV's cellular structure onto a rigid surface. A goal of this pre-test simulation was to predict the upper and lower acceleration limits of the cellular structure for impact onto a rigid concrete surface. Consequently, various failure criteria for the webs of the cellular structure, and different constitutive models were used for the foam inside each cell. Each model created for the analysis will be described. The final model that was considered the most accurate was compared with test results. The impact conditions for test #4 were approximately a 40 m/s impact onto concrete using the bungee accelerator facility at the NASA Langley Impact Dynamics Research Facility[4] (IDRF).

Instrumentation consisted of one low-g accelerometer, which was integrated to obtain the impact velocity, an accelerometer inside the OS provided by the Jet Propulsion Laboratory (JPL), an accelerometer on the top of the OS, and an accelerometer on the impact test plate. All accelerometers were oriented to measure vertical accelerations. Refer to Figure 3 for the diagram of the impact test specimen.

Pretest Model Predictions

MSC.Dytran models have been developed to predict the impact response of drop test article #4. The test specimen, which is shown in Figure 3, consists of a hemispheric cellular structure, an impact test plate on top of the hemispheric cellular structure that represents the top half of the sphere, and a simulated OS from JPL. The OS is designed to contain Mars soil and rock samples. Metric units were used in this analysis; i.e., meters, kilograms, and seconds (MKS).

Note that carbon foam was used in the cellular structure because it is an excellent energy absorbing material with near constant crush stress. It is also well suited to space applications since it is relatively inert and temperature insensitive. Two different material models were used to represent the carbon foam. First a DYMAT24 model was used. The DYMAT24 material model was used to represent the polyurethane foam that had filled the cells in the earlier, less refined drop test specimens. DYMAT24 is a general elastic-plastic material model with a non-zero Poisson ratio. The second model used to represent the carbon foam was a FOAM1 material model, which is a specialized foam material model with a Poisson ratio equal to zero. The input for the FOAM1 model was a stress-strain table with a linear elastic region, a plastic (crush) region, and a rapidly rising stress region after 90 % strain to represent compaction. Intuitively, carbon foam is expected to have a Poisson ratio near zero since the foam is a very brittle material with low shear strength. Strain-based failure criteria were used for the web (cell walls) material inside the cellular structure. Several cases were executed including no failure, 10%, 20%, and 25% plastic failure strain. For the case without web failure, the peak predicted acceleration is maximum as the structure is the strongest and the permanent deformation of the cellular structure is the smallest. Analytical results for 10% plastic

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failure strain allowed portions of the web to fail early, allow more permanent deformation, and would produce the lower-bound peak acceleration (if enough crush distance is available to prevent "bottoming-out"). For a 20 – 25% web plastic failure strain, one would expect to obtain an acceleration pulse between the two extremes.
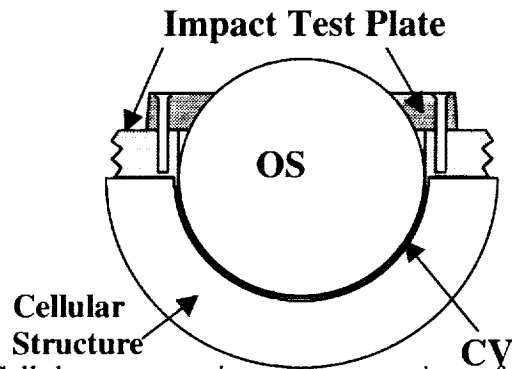
Impact Test Plate

Figure 3 – Cellular structure impact test specimen for drop test #4.

MSC.Dytran Case I – Carbon Foam Represented by DYMAT24

The model for cellular impact test #4 contained 7667 grid points and 8720 elements. Shell elements are used to represent the graphite/epoxy/Kevlar web, the inner and outer hemispherical skins of the cellular-structure, and the OS titanium container. Solid elements are used to represent carbon foam, the OS conforming foam, and the impact test plate at the top of the structure. The finite element model is illustrated in Figure 4. The cell-wall (web) material was modeled to be elastic-plastic, but was not allowed to fail.
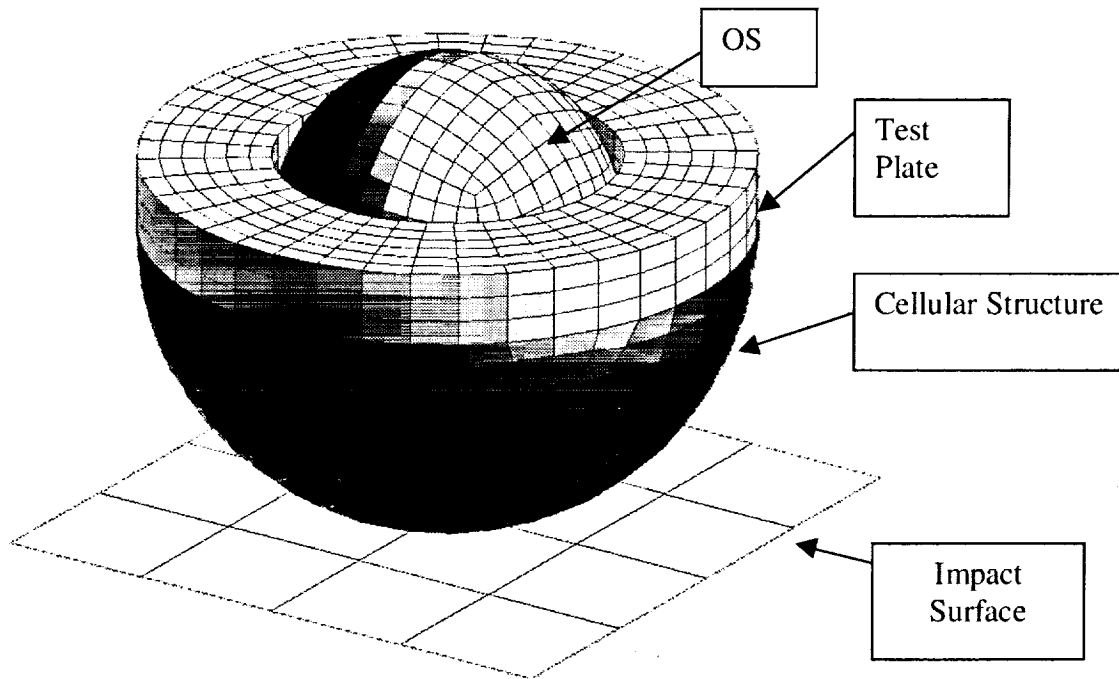
Figure 4 – Model of OS, cellular structure, and impact plate for cellular impact test #4.

For simplicity, the OS sample container was considered a rigid body. The material properties for the OS model were taken from the JPL LS-Dyna model. Two contact surfaces were required in the model: 1) contact between the OS and the cellular structure and 2) contact between the combined OS /cellular structure with the impact surface. The total mass of the model is assumed to be approximately 14 kg. The OS mass (foam + cannister) as received from JPL is 2.374 kg, the containment vessel (CV) mass is 0.1334 kg, and the metallic OS cannister is assumed to weigh about 1.76 kg. The CV is additional protective material (Kevlar fabric) that is between the cellular structure and the OS. The mass breakdown is shown in the Table I below:

Table Ia. – Density, Volume, and Mass of Cellular Structure Components

Component	Density (kg/m^3)	Volume (m^3)	Mass (kg)
Carbon foam	48.0	6.5e-3	0.317
Webs	1539.0	9.4e-4	1.448
Sphere outer skin	1379.0	7.8e-5	0.108
Sphere inner skin	1550.	6.3e-5	0.097

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OS foam	460.0	1.3e-3	0.605
CV			0.1334
OS metal parts without foam	Rigid Ixx, Iyy, Izz About .004 kgm^2		1.760
Impact plate	4750.	2.0e-3	9.5
TOTAL			14.0

Table Ib. – Material Models of Cellular Structure Components

Material	Effective E (N/m^3)	Poisson Ratio	Yield (N/m^3)	Material model
Carbon foam	1.379e8	0.3	1.379e6	DYMAT24
Webs 18 layers (Hybrid Graphite-Epoxy /Kevlar)	1.379e10	0.3	1.379e8	DYMAT24
Kevlar	6.895e9	0.3	1.034e8	DYMAT24
Graphite-epoxy	4.55e10	0.3	5.79e8	DYMAT24
OS foam	4.38e8	0.334	1.54e7	DYMAT24
Impact plate	2.72e10	0.3	2.68e8	DYMAT24

The model was run on a single processor of a Sun Ultra Enterprise 450 workstation and required approximately 1 hour of CPU time. The predicted acceleration of the OS is shown in Figure 5. The solid line is the MSC.Dytran OS model output acceleration at 50,000 samples per second. The broken line was obtained by filtering the MSC.Dytran output with a 1000 Hz low-pass filter. The filtered response curve shows that the acceleration rapidly climbs to 2500 g's in 0.5 ms and increases to a maximum of slightly over 4000 g's at 1.5 ms. The pulse duration is 0.002 seconds (2 ms). Since failure of the webs was not allowed, this response can be assumed to be the **upper limit acceleration pulse**.

The deformed plots of the model are illustrated in Figure 6 for 1 ms and 2 ms. Maximum crushing of 3.7 cm (1.47 in.) occurs at 1.5 ms.
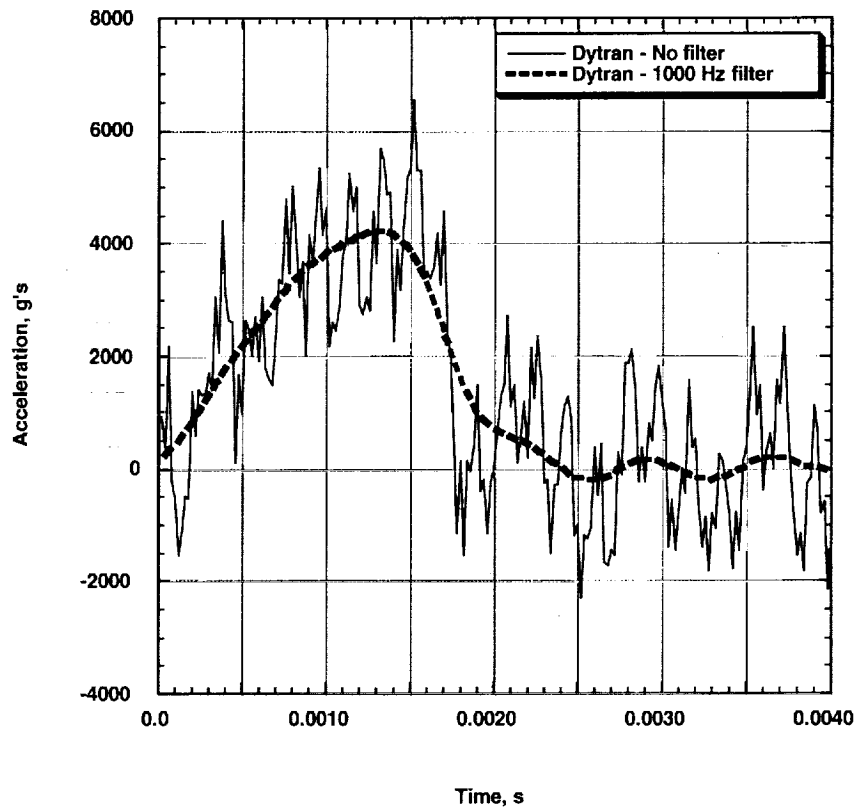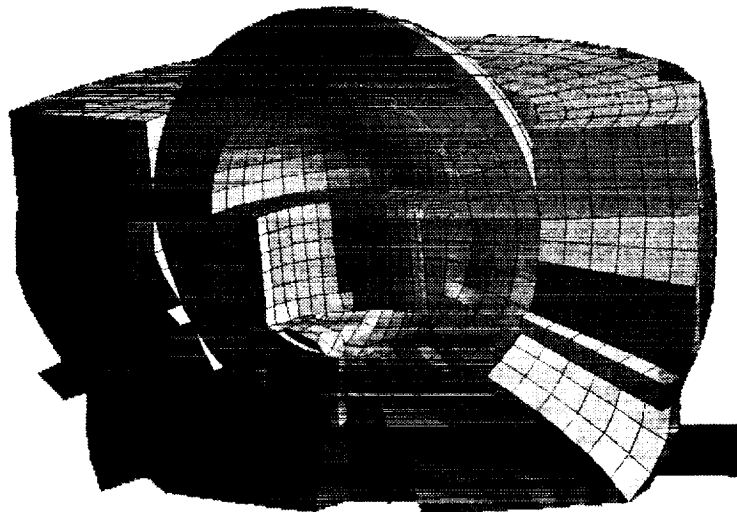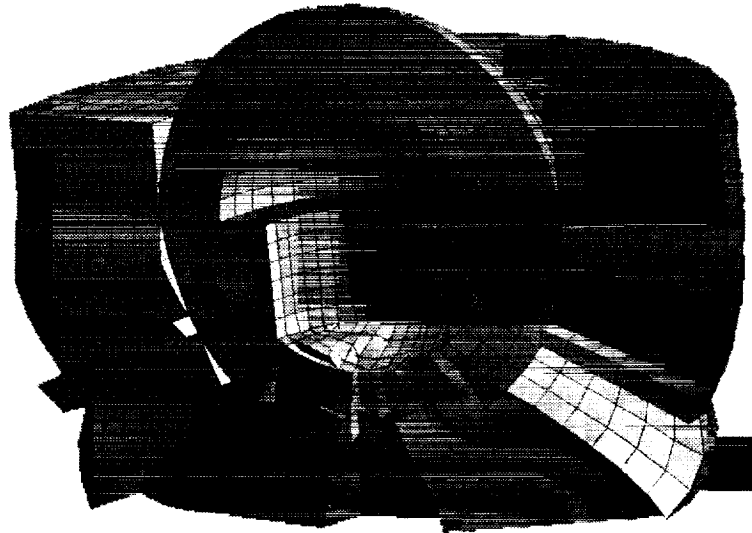
Figure 5 - Predicted OS acceleration for DYMAT24 carbon foam, 40 m/s impact. No failure of cell-wall material. This curve is the **upper limit** acceleration pulse.

a. Time = 0.001

b. Time = 0.002

Figure 6 - Deformed plots of the model with color-coded displacement.

The initial model was modified to capture the actual tearing and crushing of the lower hybrid cellular structure. The OS acceleration for the model with a failure strain of 0.10 is shown in Figure 7. The dashed line shows the MSC.Dytran data filtered with a 1000 Hz low-pass filter. With the failure strain applied, elements are deleted when the strain exceeds 0.10. Thus, the initial acceleration is lowered and a plateau forms around 2500 g's. However, a secondary stiffening occurs which briefly causes the acceleration to approach 3500 g's for a short amount of time. It is not certain that the model deformation pattern correctly predicts the actual test article for these large deformations due to the complexity of the energy absorbing mechanisms. In addition to foam crushing, which is relatively simple, the web energy absorbing mechanisms include crushing, delamination, complex bending, tearing, etc. The present model does not include delamination or tearing behavior and retains too much elastic energy. Some studies were performed to simulate tearing using BJOIN elements that break under a specified failure condition. However, numerical problems developed and the BJOIN elements were removed for this simulation study.
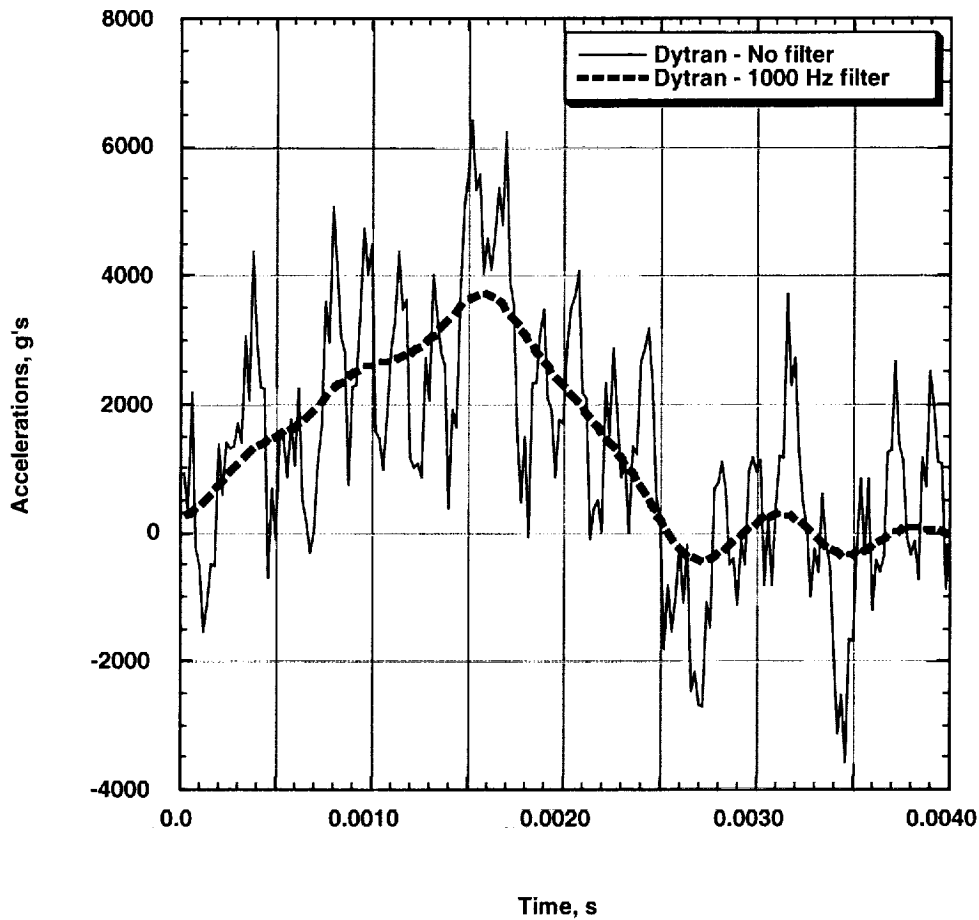
Figure 7 – Predicted OS acceleration for 40 m/s impact. Cell-wall failure strain is 10 %.

The model was also run with a 25 % plastic failure strain. A comparison of displacements of the OS for no failure, 10 %, and 25 % web failure strains is shown in Figure 8. As would be expected, the largest displacement for a 25% plastic failure strain corresponds to the lowest acceleration pulse. The velocity data for the same three cases are shown in Figure 9. Note that the information from Figure 9 predicts a rebound velocity of about 10 m/s. This high rebound velocity indicates that a lot of elastic energy was stored, and would predict that the structure would rebound about 4 meters. It is very unlikely that the structure will rebound such a distance. Consequently, it is expected that the acceleration response will over-predict the actual experimental results for this model.
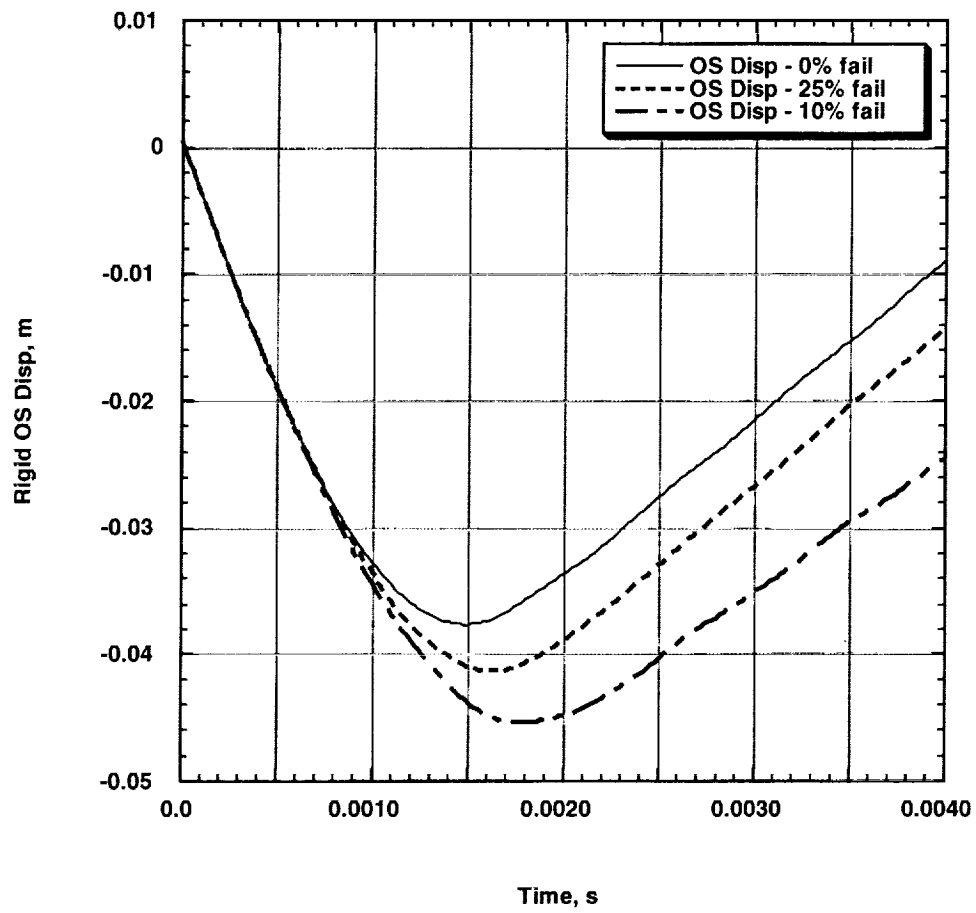
Figure 8 – Predicted OS displacement for models with cell-wall plastic failure strain of 0, 10 %, and 25%.
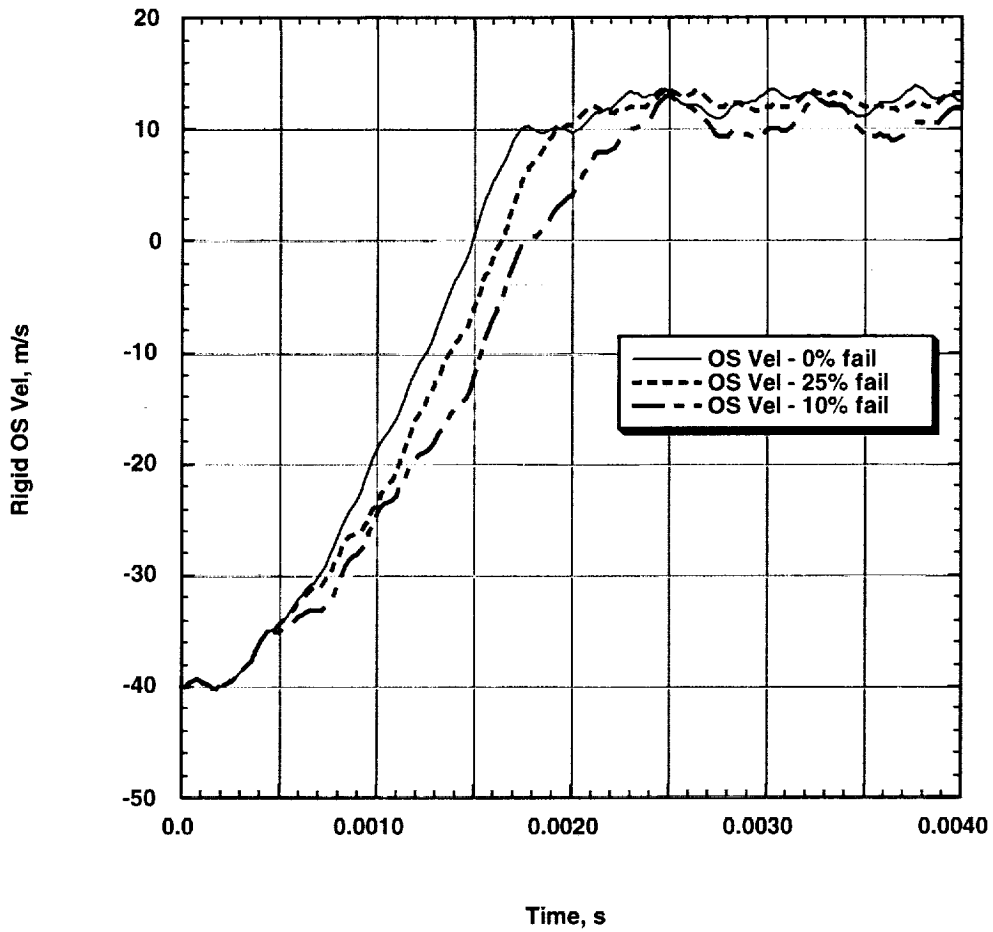
Figure 9 – Predficted OS velocity for models with plastic failure strain of 0, 10 %, and 25%.

The predicted acceleration for the impact plate location is shown in Figures 10 and 11 for the model with no failure. This acceleration has a high vibration content, and the underlying impact pulse is not apparent until the data is filtered. The impact plate acceleration is slightly higher than the predicted OS acceleration.
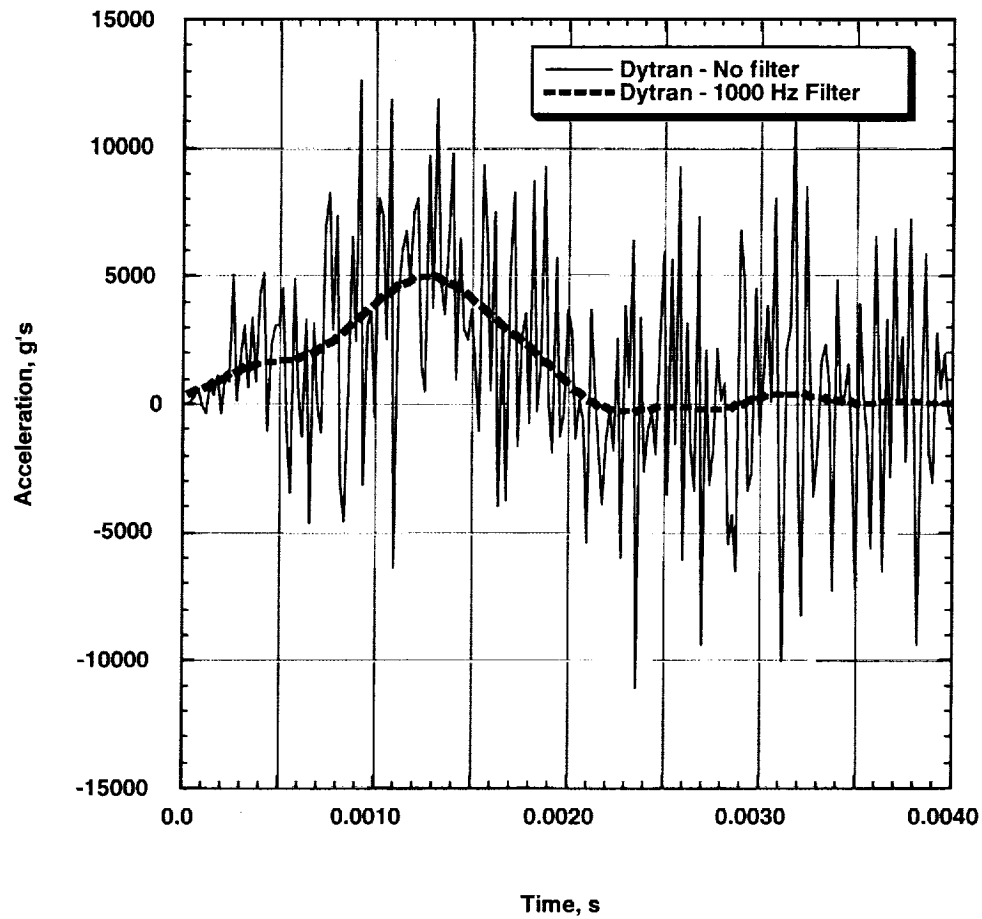
Figure 10 – Predicted acceleration on impact plate at top of cellular structure without web failure.
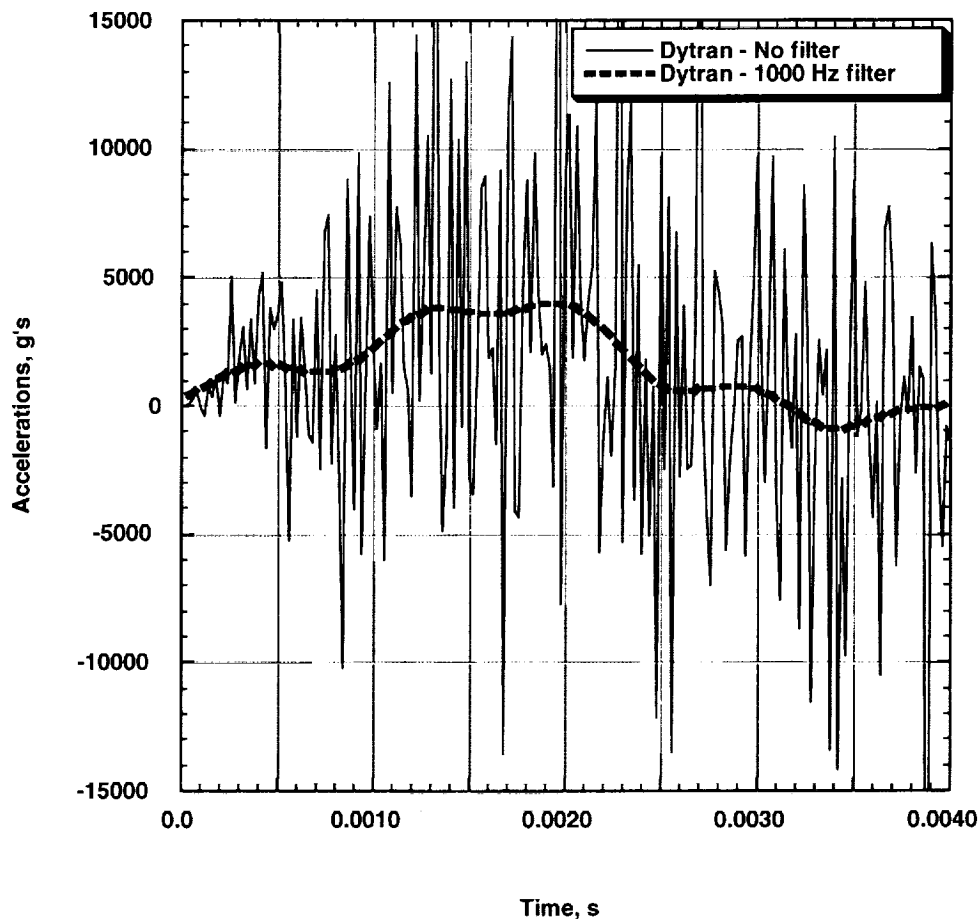
Figure 11 – Predicted acceleration of impact plate at top of cellular structure for 10% plastic failure strain.

Case II. Carbon Foam Material Represented with FOAM1

The models in Case I consistently showed too much rebound velocity. Also, Poisson's ratio was set to 0.3 for the DYMAT24 material card used to represent carbon foam as low values of Poisson's ratio give undesirable results. Thus, a more realistic foam material model was needed to represent the carbon foam. The FOAM1 material model in MSC.Dytran is recommended for large amounts of crushing for materials such as foams with a near zero Poisson ratio. Thus, the model was modified to incorporate FOAM1 to represent the carbon foam. No other changes were made to the original model. The use of the FOAM1 material required input of the bulk modulus and a table of the crush stress versus "crush displacement." To prevent negative volume, a very large compaction stress was included for crush greater than 90 percent.

The predicted vertical acceleration response of the OS using the FOAM1 material model is shown in Figure 12, assuming no failure of the cell walls.   The solid line is the predicted MSC.Dytran acceleration output for the OS at 50,000 samples per second. The broken line was obtained by filtering the predicted results with a 1000 Hz low-pass filter. The filtered response curve shows that the acceleration rapidly climbs to 3000 g's in less

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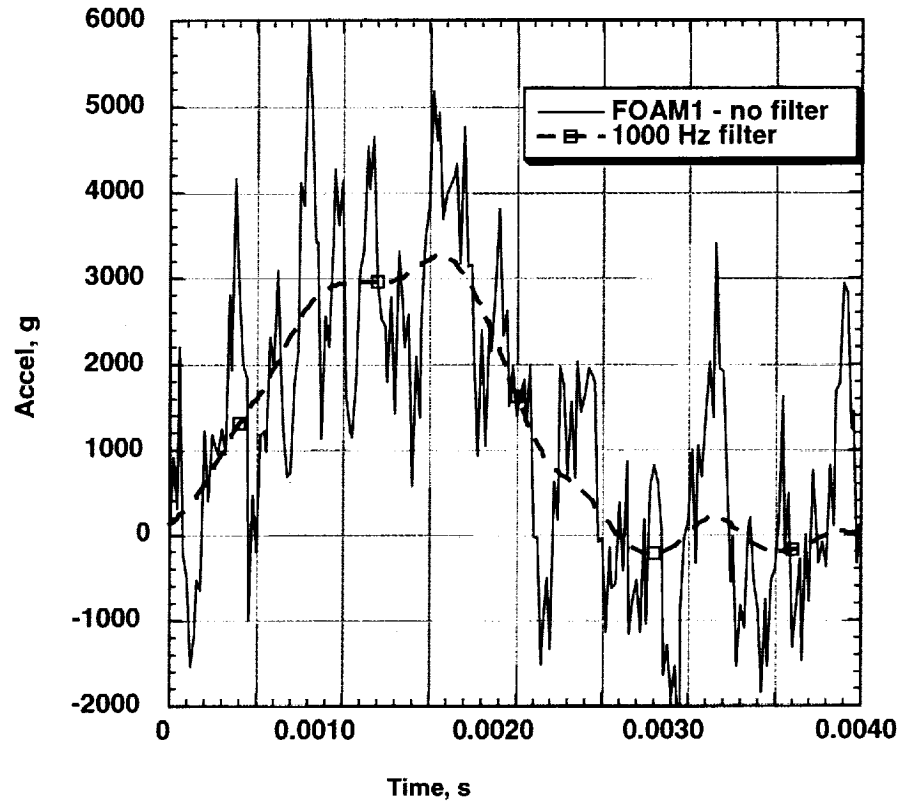than 1.0 ms and increases to a maximum of slightly over 3200 g's at 1.5 ms. The pulse duration is 2.6 ms.

Figure 12 - OS acceleration for FOAM1 representation of carbon foam, no failure of cell-wall material.

It is informative to compare the OS acceleration of the model without cell wall failure with the FOAM1 representation of carbon foam (Figure 12) with the same model using DYMAT24 to represent the carbon foam (Figure 5). Note that the filtered acceleration peak drops from slightly over 4000 g's for the DYMAT24 representation to slightly over 3000 g's for the FOAM1 representation. The deformation of the lower portion of the cellular structure is shown in Figure 13 for times of 1, 2, and 3 ms. At the time of 3 ms, the hemisphere is rebounding. Again, compare the deformed shape in Figure 13 with the deformation in Figure 6. Note that the deformed shape of the bottom of the cellular structure in Figure 6 is more complex than for that shown in Figure 13 where the FOAM1 model is used. The non-zero Poisson ratio material model for the carbon foam may be responsible for the more complex folding and bulging observed in Figure 6.

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Time = 0.0   Time = 1 ms

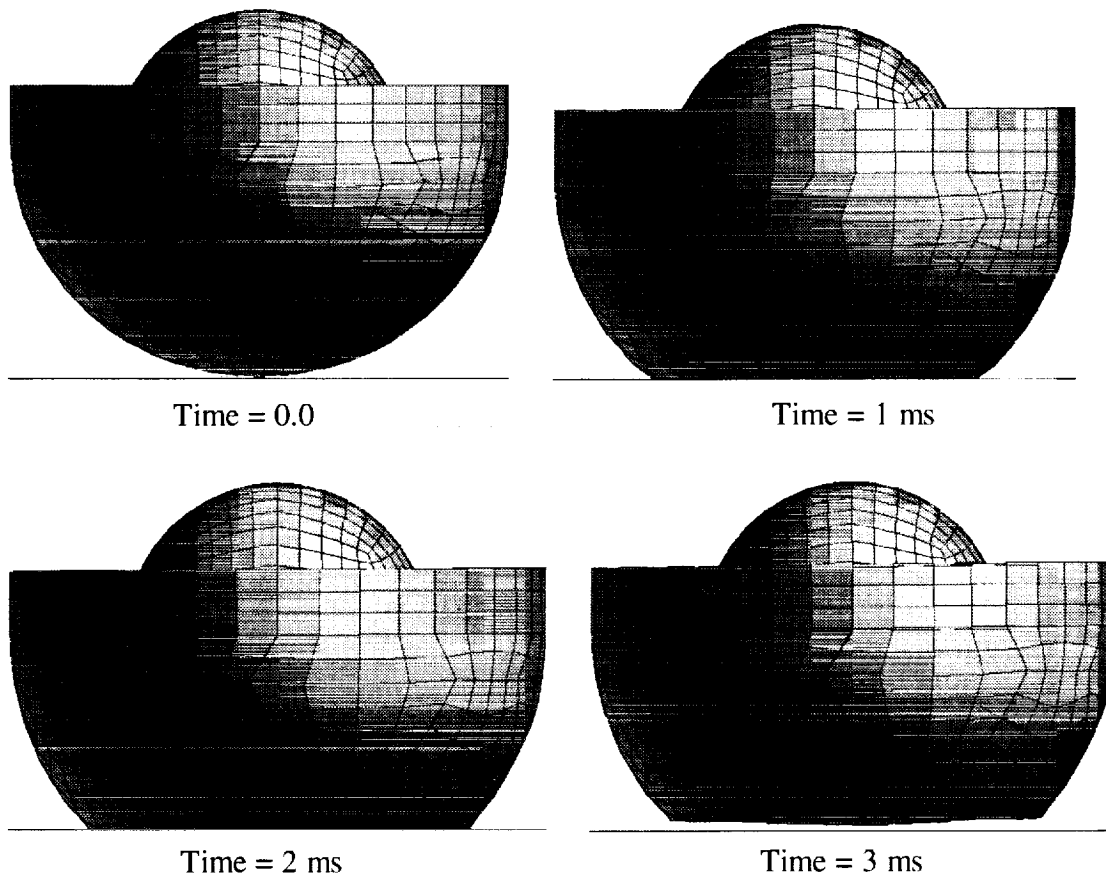Time = 2 ms   Time = 3 ms

Figure 13 – Four deformed shape plots of the cellular structure for time equal 0 to 3 ms. Note that there is minimal bulging of the bottom of the hemisphere.

In Figure 14, the predicted acceleration response of the OS is shown using the FOAM1 material model to represent the carbon foam with a 20% plastic failure strain for the web elements. The cellular structure deformation predicted for the 20% web strain failure is at least 90 % of the allowable stroke. Consequently, a 10% failure strain model was not run as the cellular structure would be too weak with insufficient stroking distance available to stop the OS without bottoming out. From this new model, the minimum acceleration peak is now expected to be within a 2000 – 2500 g range, and with a pulse duration of about 3.5 ms.
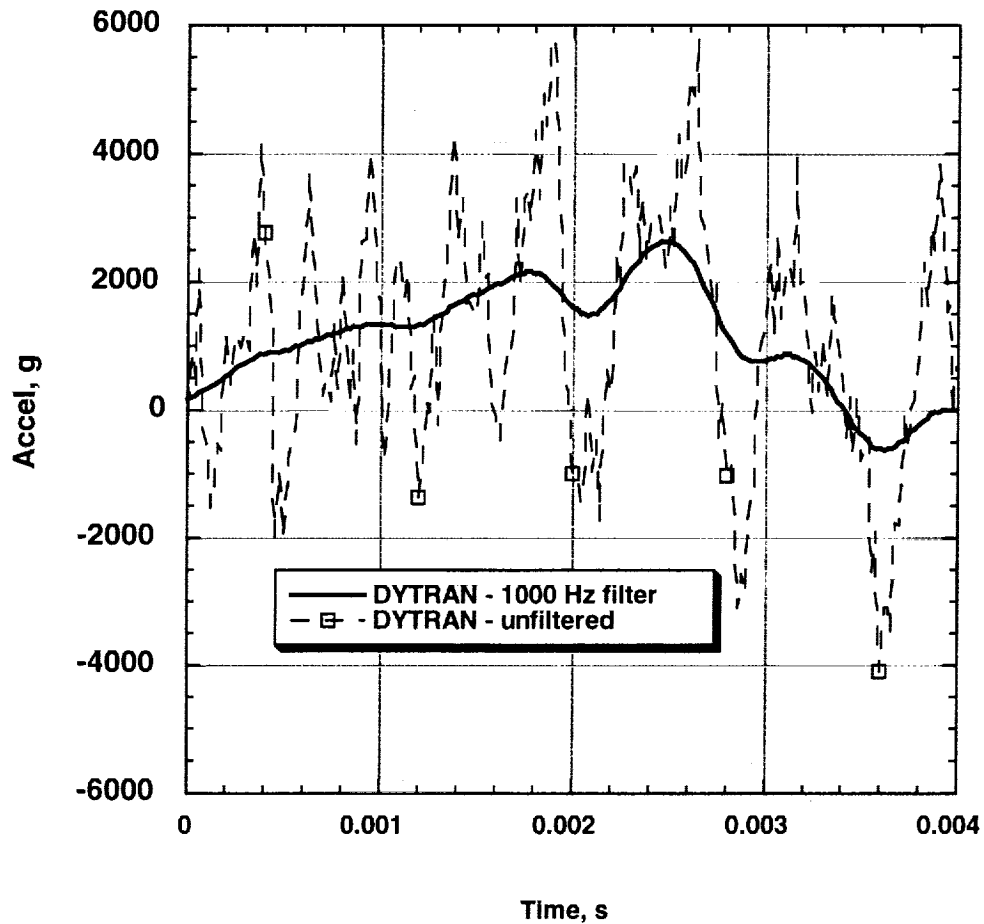
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Figure 14 – Predicted OS acceleration for a 20% cell-wall failure strain criteria and a
FOAM1 carbon foam material model..

Since the FOAM1 model produced better deformation results and had less rebound
velocity, the last two predictions shown in Figures 12 and 14 should bound the impact
test #4 experimental data. Consequently, it is expected that the peak acceleration input to
the OS should range from 2500 g's to slightly over 3000 g's. Since the 3000-g value is
highly conservative with the no web failure criteria, the 2500-g value is more likely to be
the best prediction for the acceleration response.

Post-Test Comparisons

Two drop tests were performed, designated cellular impact test 4a and 4b, respectively by the test engineer. The results from drop test 4a will not be used due to problems with the data acquisition system and with the manufacture of the cellular impact model itself.

The Two Body Interaction
The containment vessel (CV) provides the coupling between the OS and the cellular structure. The measured accelerations at the top of the OS and on the top surface of the impact test plate for test 4b (from now on referred to as test #4) are shown in Figure 15. Note that there is a time delay of approximately 0.0005 s from the beginning of the plate/cellular structure acceleration to the initiation of the OS acceleration. This delay is due to the highly nonlinear CV material, which fills the gap between the OS and the cellular structure. In addition, the relatively large spikes at the end of the traces of the impact test plate and the OS are due to impact of the OS with the impact test plate. Consequently, to evaluate the actual dynamic response of the cellular structure and to remove the interaction between the two bodies, the following equation was developed,

$$F(t) = A_{CS}M_{CS} + A_{OS}M_{OS} = M_{TOTAL}A_{SYS}$$

Where $F(t)$ is the crush force of the cellular structure, A_{CS} is the measured acceleration of the combined plate and cellular structure, A_{OS} is the measured acceleration of the OS, and A_{SYS} is the system acceleration (or the acceleration at the cg of the system).

Solving for the system acceleration:

$$A_{SYS} = (A_{CS}M_{CS} + A_{OS}M_{OS}) / M_{TOTAL}$$

For the equation to apply, it was assumed that the impact test plate is rigidly attached to the cellular structure and that the mass of the crushed portion of the sphere is small compared with the total mass. By using the system acceleration, the peaks due to the two separate bodies are eliminated (see Figure 15), and thus a better representation of the behavior of the cellular structure for a "perfect CV coupling" is obtained. Consequently, the CV was incorporated in the OS model by coupling the OS to the cellular structure with equivalent nodes. This approach represented a slight change from the original model.
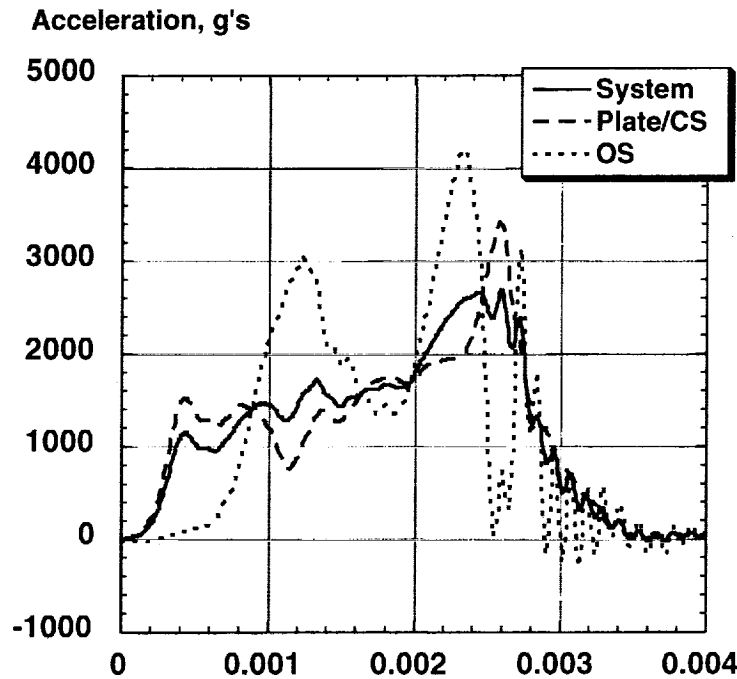
Acceleration, g's

Figure 15 – Measured accelerations for cellular structure drop test of the OS, plate/CS, and the calculated system acceleration.

The results from the FOAM1 model shown in Figure 14, which was expected to be the best pre-test model, predicted a peak system acceleration of approximately 2,600 g's, which occurred at approximately 2.5 ms into the impact simulation. This result compares well with the measured system peak system acceleration of 2,700 g's. Overall, the simulation accurately predicted the shape, magnitude, and duration of the measured system acceleration pulse, as shown in Figure 16 when the analysis is plotted with the experimental system acceleration. Note that the OS and the cellular structure were coupled together without a CV material for this analysis.
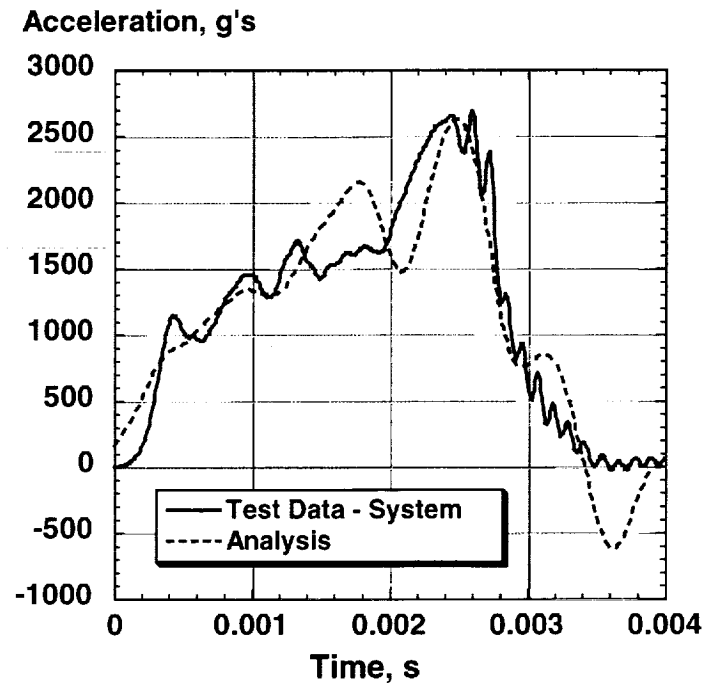
Acceleration, g's

Figure 16 - Comparison of numerical and measured system acceleration for cellular drop
test #4.

The total crush stroke of the finite element simulation was 0.063 m, or approximately
90% of the available crush distance for the cellular structure. The crush of this test
specimen was difficult to measure post-test, as the deformed cell walls sprung back, and
the outer skin fold lines were not as defined as in the previous tests. However, the crush
was estimated to be approximately 90%. A deformed plot of the finite element model
showing the maximum stroke is shown in Figure 17. A photograph of the cellular
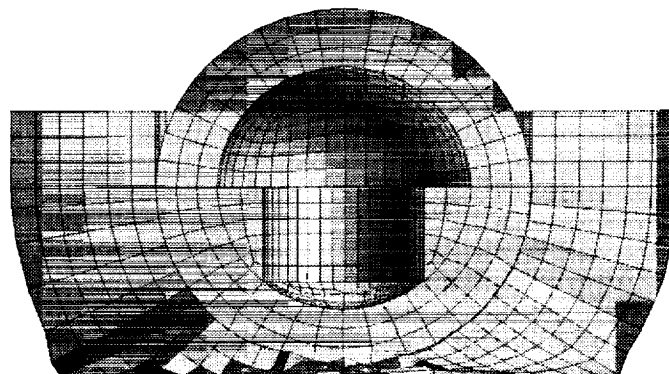structure after the impact is shown in Figure 18.

Figure 17 – Deformed plot from finite element simulation showing max crush at 3 ms.

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Figure 18 – Photograph of cellular structure cross section, post test.

Concluding Remarks

The nonlinear, transient dynamic finite element code, MSC.Dytran, was used to model the acceleration pulse for the impact test of an energy absorbing cellular structure. This pre-test simulation was performed to aid in developing an energy absorbing concept for a highly reliable, passive Earth Entry Vehicle (EEV) designed to impact the Earth's surface without a parachute. In addition, a goal of the simulation was to determine an upper and lower bound for the acceleration pulse produced at impact and transmitted to the simulated space cargo container. The material model used to represent the foam and the proper failure criteria for the cell walls were critical in predicting the impact loads of the cellular structure. The first material model for the foam (DYMAT24) did not properly account for the near-zero Poisson ratio of the carbon foam material. Also, since the finite element results have extremely high frequency oscillations superimposed on the acceleration pulse, low-pass digital filtering is required to extract the fundamental acceleration pulse. Pre-test predictions to determine the maximum acceleration pulse were based on no failure for the cellular structure webs. This assumption gave a maximum pulse acceleration of approximately 3000 g's using the FOAM1 model for the carbon foam. The minimum expected pretest acceleration was based on a failure strain slightly less than 20%. The minimum pulse acceleration based on this model was predicted to be approximately 2000 g's.

It was determined that a FOAM1 model for the foam and a 20% failure strain criteria for the cell walls correlated best with the acceleration pulse for drop test #4. When the cellular structure and OS are modeled separately, the acceleration of each component is complicated due to a two-body interaction. To make meaningful comparisons between analysis and test, a mass-weighted system acceleration of the cellular structure and OS was used. This comparison allowed the acceleration response of the impact test specimen to be determined for a "near perfect" coupling between the OS and cellular structure.

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The predicted peak system acceleration using 20 % failure strain for the webs and a FOAM1 model for the carbon foam is approximately 2,600 g's. This predicted value compares well with the measured system peak system acceleration of 2,700 g's. Overall, the simulation accurately predicted the shape, magnitude, and duration of the measured system acceleration pulse and has proved to be an extremely valuable design tool.

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11. Abstract
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